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NGC 1614: A LABORATORY FOR STARBURST EVOLUTION

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ABSTRACT

The modest extinction and reasonably face-on viewing geometry make the luminous infrared galaxy NGC 1614 an ideal laboratory for study of a powerful starburst. *HST*/NICMOS observations show: 1.) deep CO stellar absorption, tracing a starburst nucleus about 45 pc in diameter; 2.) surrounded by a ~ 600 pc diameter ring of supergiant H II regions revealed in Pa α line emission; 3.) lying within a molecular ring indicated by its extinction shadow in $H - K$; 4.) all at the center of a disturbed spiral galaxy. The luminosities of the giant H II regions in the ring are extremely high, an order of magnitude brighter than 30 Doradus; very luminous H II regions, comparable with 30 Dor, are also found in the spiral arms of the galaxy. Luminous stellar clusters surround the nucleus and lie in the spiral arms, similar to clusters observed in other infrared luminous and ultraluminous galaxies. The star forming activity may have been initiated by a merger between a disk galaxy and a companion satellite, whose nucleus appears in projection about 300 pc to the NE of the nucleus of the primary galaxy. The relation of deep stellar CO bands to surrounding ionized gas ring to molecular gas indicates that the luminous starburst started in the nucleus and is propagating outward into the surrounding molecular ring. This hypothesis is supported by evolutionary starburst modeling that shows that the properties of NGC 1614 can be fitted with two short-lived bursts of star formation separated by 5 Myr (and by inference by a variety of models with a similar duration of star formation). The total dynamical mass of the starburst region of $1.3 \times 10^9 M_{\odot}$ is mostly accounted for by the old pre-starburst stellar population. Although our starburst models use a modified Salpeter initial mass function (turning over near $1 M_{\odot}$), the tight mass budget suggests that the IMF may contain relatively more 10 - 30 M_{\odot} stars and fewer low mass stars than the Salpeter function. The dynamical mass is nearly 4 times smaller than the mass of molecular gas estimated from the standard ratio of ^{12}CO (1 - 0) to H_2 . A number of arguments place the mass of gas in the starburst region at $\sim 25\%$ of the dynamical mass, nominally about 1/15 and with an upper limit of 1/10 of the amount estimated from ^{12}CO and the standard ratio.

Subject headings: Galaxies: nuclei – Galaxies: individual: NGC1614 – Galaxies: active galaxies: photometry – galaxies: stellar content – infrared: galaxies

1. INTRODUCTION

Numerical simulations of collisions between gas-rich galaxies (e.g., Barnes & Hernquist 1996 and references therein) and even minor mergers between a gas-rich galaxy and a satellite companion (e.g., Mihos & Hernquist 1994) show that these processes are very efficient in transporting large quantities of molecular gas into the galaxy nuclei. As a result of the concentration of gas, a strong burst (or various bursts) of star-formation may occur, and an AGN may be activated, as observed in many infrared luminous and ultraluminous galaxies (LIRGs and ULIRGs). Sanders et al. (1988) suggested that the LIRG and ULIRG galaxies are the initial stage for the appearance of a quasar (see also the review by Sanders & Mirabel 1996). However, recent results from mid-infrared spectroscopy seem to indicate that most LIRGs and many ULIRGs may be powered by star formation (Lutz et al. 1999). These objects therefore

allow probing the process of star formation on an extreme scale and intensity.

NGC 1614 (Arp 186) is relatively nearby (distance $D = 64$ Mpc for $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and has a high infrared luminosity ($L_{\text{IR}} = 3 \times 10^{11} L_{\odot}$, which places this system in the luminous infrared galaxy category). The galaxy shows a spectacular outer structure with tidal tails or plumes (see e.g., Neff et al. 1990 and also Figure 1) suggesting that this morphology is the result of an earlier interaction/merger process with another galaxy. Neff et al. (1990) collected optical, near-infrared and radio observations for this galaxy and found no evidence for the presence of active galactic nucleus (AGN), making it an excellent laboratory for study of a very luminous starburst.

We present *HST*/NICMOS near infrared observations of NGC 1614, giving unprecedented angular resolution on the galaxy for this spectral region. These new observations

TABLE 1
LOG OF THE *HST* OBSERVATIONS.

Camera	Filter	scale	t_{exp}	filter/line
NIC1	F110M	0.043	384	pseudo- <i>J</i>
NIC2	F160W	0.076	192	<i>H</i>
NIC2	F222M	0.076	640	<i>K</i>
NIC2	F187N	0.076	640	continuum
NIC2	F190N	0.076	640	$\text{Pa}\alpha$
NIC2	F212N	0.076	1792	continuum
NIC2	F215N	0.076	1792	H_2
NIC2	F237M	0.076	960	CO absorption
WFPC2	F606W	0.041	500	<i>R</i>

NOTE.—Column (1) is the camera. Column (2) is the filter. Column (3) the plate scale in arcsec pixel⁻¹. Column (4) is the total integration time in seconds. Column (5) is the corresponding ground-based filter, or the emission line.

are combined with an archival *HST*/WFPC2 red image, ground-based near infrared spectroscopy, and results from the literature to probe the starburst.

2. OBSERVATIONS

2.1. *HST*/NICMOS Observations

HST/NICMOS observations of NGC 1614 were obtained in February 1998 using cameras NIC1 and NIC2. The pixel sizes are 0.043" pixel⁻¹ and 0.076" pixel⁻¹ respectively. Table 1 lists details of the observations. Standard data reduction procedures were applied (see Alonso-Herrero et al. 2000a for more details). The flux calibration was performed using the conversion factors based on measurements of the standard star P330-E during the Servicing Mission Observatory Verification (SMOV) program.

The fully-reduced images were rotated to the usual orientation with north up, east to the left. They are shown in Figure 2. In addition, we constructed an infrared color map using the NIC2 F160W and NIC2 F222M images, which is equivalent to a ground-based *H* – *K* color map. In the NIC1 F110M image (highest angular resolution) the nucleus of NGC 1614 appears to be slightly resolved with a FWHM of 0.15" (or 45 pc for the assumed distance), whereas for the unresolved sources (the stellar clusters discussed in Section 3.2) we measured FWHMs of approximately 0.11" (or 35 pc).

The continuum subtracted $\text{Pa}\alpha$ image was produced by a straight subtraction of the flux calibrated NIC2 F187N image (continuum) from the flux calibrated NIC2 F190N image (line+continuum). NICMOS only provides narrow continuum bands to one side of the emission line. For NGC 1614 the continuum image lies to the blue, and therefore if some extinction is present the continuum at the emission line wavelength may be slightly over-subtracted. Table 2 gives the photometry of the H II regions in the ring of star formation and the brightest ones along the spiral arms.

A continuum subtracted H_2 image was produced in a

similar manner, using the F212N (continuum) and F215N (line+continuum) filters. Because the H_2 line is relatively weak, the image subtraction near the nucleus is not reliable. Artificial images of point sources were generated for both filters and used in experiments to determine where useful information could be obtained. Based on these experiments, we have excluded the data within 0.25" of the nucleus from further analysis. Figure 3 shows the surface brightness in $\text{Pa}\alpha$ compared with that in the (1,0) S(1) H_2 line at $\lambda_{\text{rest}} = 2.12 \mu\text{m}$. We have averaged the data along an artificial slit 0.61" in width and oriented at position angle 170° selected to avoid the secondary nucleus and the brightest H II regions in the circumnuclear ring (see below). The H_2 extends farther out from the nucleus than does the $\text{Pa}\alpha$.

Alonso-Herrero et al. (2000a) discuss a NICMOS CO photometric index (defined as $\text{CO}_{\text{NICMOS}} = \frac{f(\text{F222M}) - f(\text{F237M})}{f(\text{F222M})}$, where the fluxes $f(\text{F222M})$ and $f(\text{F237M})$ are in Jy). The spatial profile of this index is shown in Figure 4 together with the $\text{Pa}\alpha$ line emission (upper panel) and the NIC2 F222M (*K*-band) brightness profile (lower panel). The errors in the CO index account for the background subtraction uncertainties in both the NIC2 F222M and NIC2 F237M filters. The nominal errors of the $\text{Pa}\alpha$ and NIC2 F222M profiles are smaller than the size of the symbols.

2.2. *HST* archival data

A Wide Field Planetary Camera 2 (WFPC2) image of NGC 1614 was retrieved from the *HST* data archive. This image was taken through the F606W filter in November 1994. Standard pipeline reduction procedures were applied. Because only a single exposure was taken for this galaxy, the cosmic rays are particularly difficult to remove, especially the extended ones. The image is saturated in the center. We rotated the cleaned image to the usual orientation (see Figure 1).

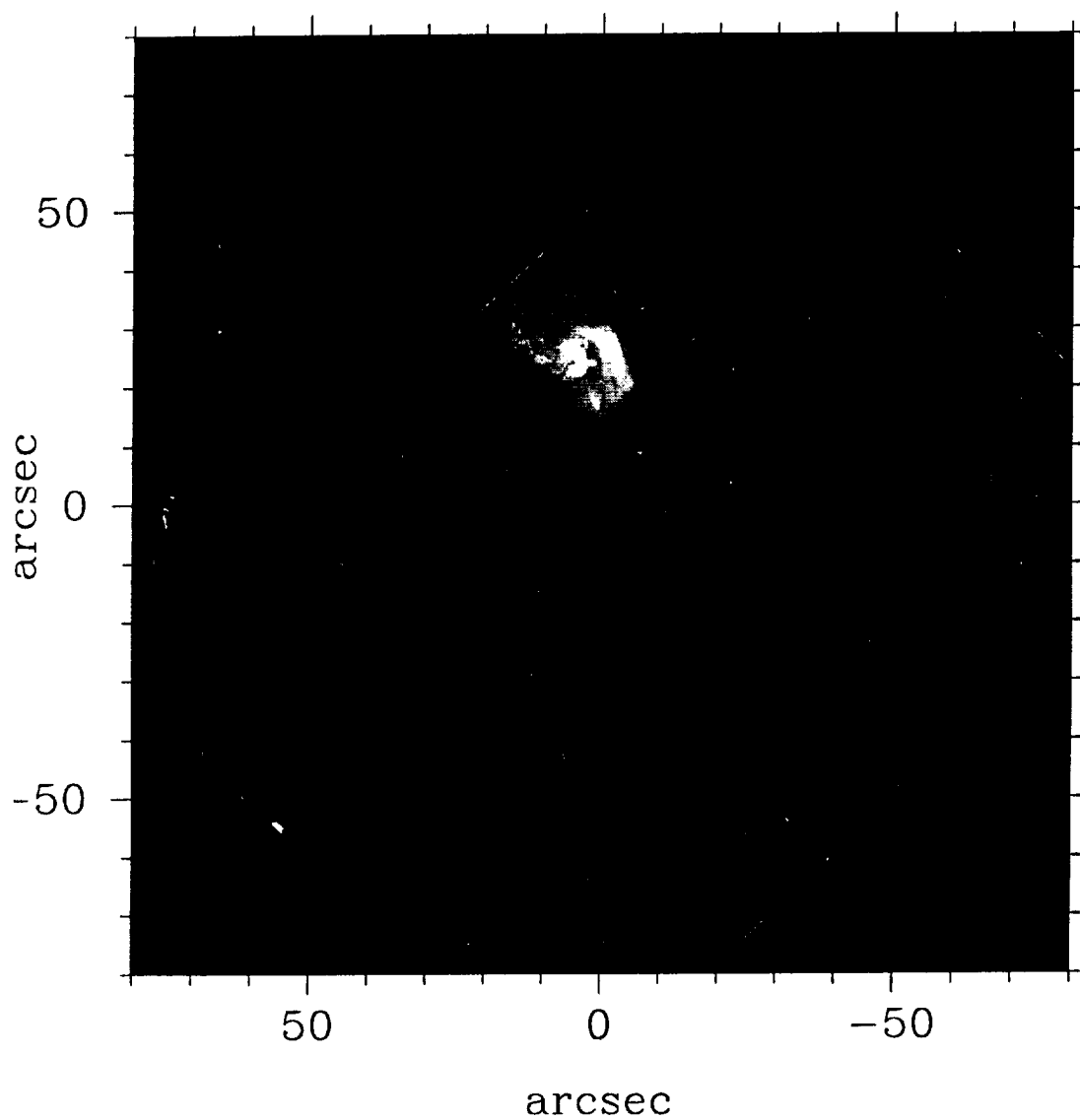


FIG. 1.— An *HST*/WFPC2 F606W (optical) image of NGC 1614 displayed on a logarithmic scale. The field of view is approximately $160''$ on a side. The orientation is north up, east to the left.

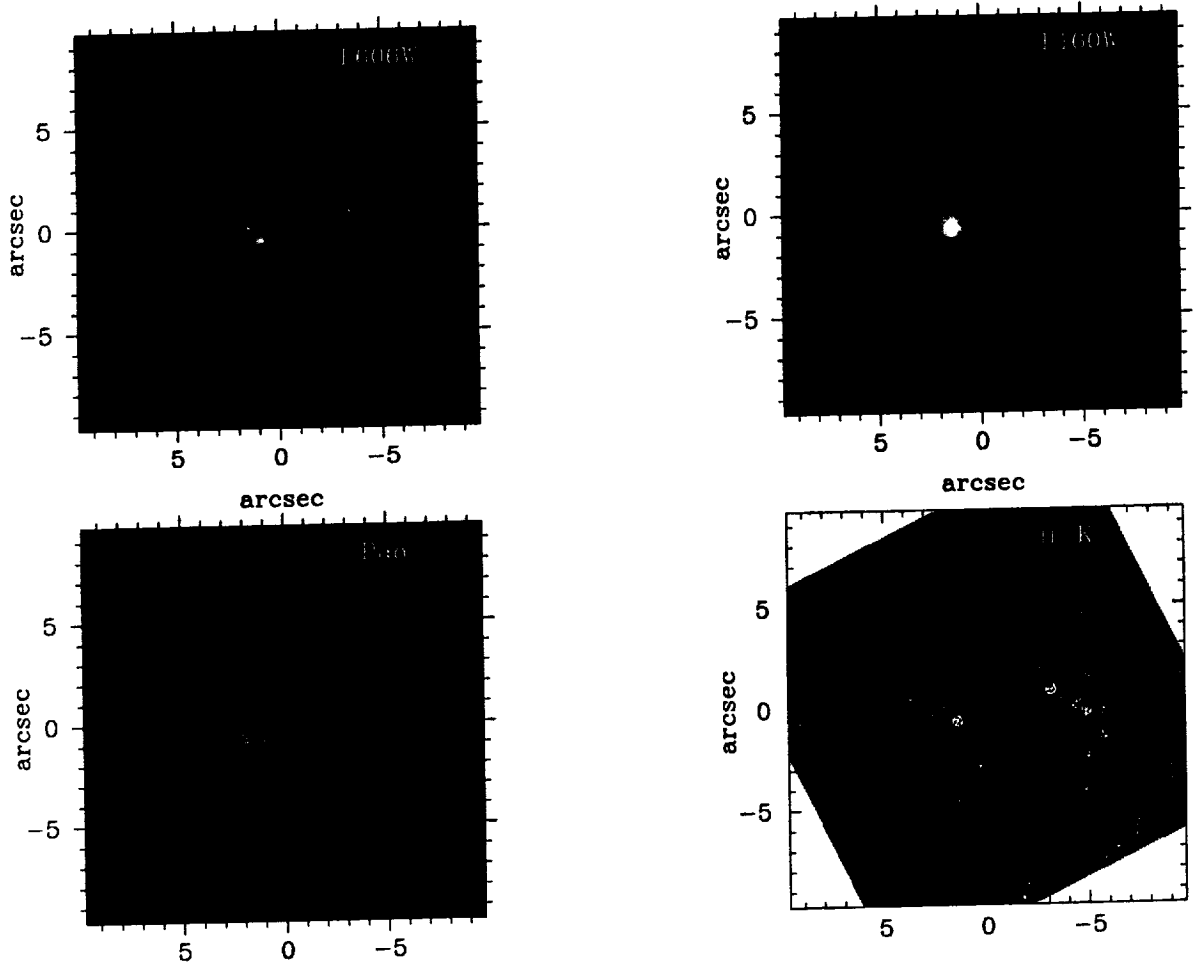


FIG. 2.— From left upper corner clockwise: WFPC2 F606W (optical), NIC2 F160W (infrared H -band), NIC2 F160W - F222M ($H - K$ color map), and line emission (continuum subtracted) $\text{Pa}\alpha$ (at $\lambda_{\text{rest}} = 1.87 \mu\text{m}$) images. The orientation is north up, east to the left. The field of view is $19.5'' \times 19.5''$. In the $H - K$ color map the dark colors indicate regions of higher extinction, with values of the K -band extinction ranging from $A_K = 0.3 \text{ mag}$ (white) to $A_K = 1.2 \text{ mag}$ (black).

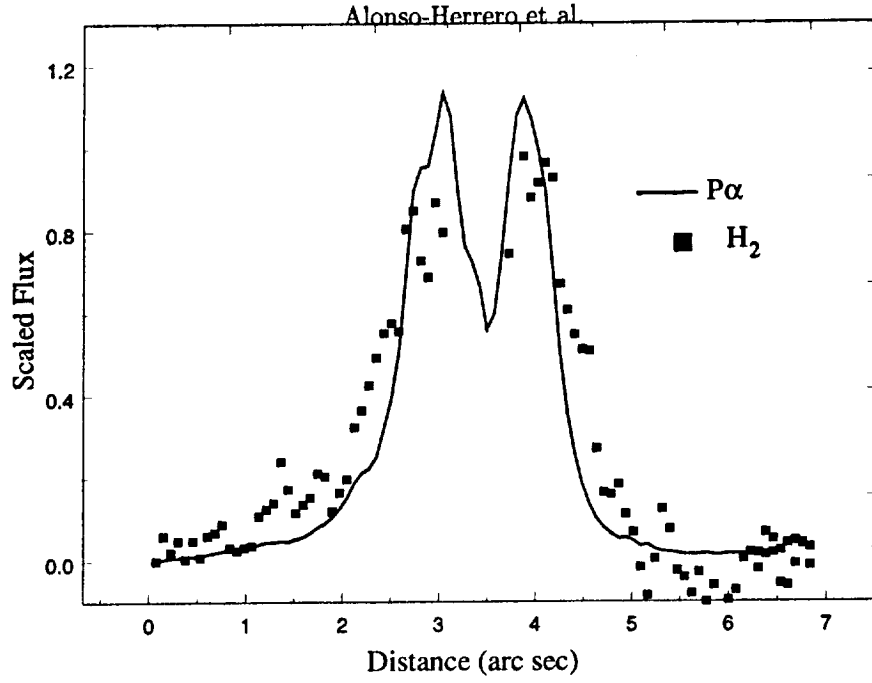


FIG. 3.— Comparison of the profile through the nucleus of the $\text{Pa}\alpha$ and $(1,0)\text{S}(1)$ H_2 emission. The data were extracted from the narrow band NICMOS images in each line by averaging across the nucleus with a width of $0.61''$ oriented at position angle 170° .

TABLE 2
H II REGIONS.

#	Δ R.A. (s)	Δ Dec. ($''$)	$f(\text{Pa}\alpha)$ ($\text{erg cm}^{-2} \text{s}^{-1}$)	$\log L(\text{Pa}\alpha)$ (erg s^{-1})	$\log N_{\text{Ly}}$ (s^{-1})
ring H II regions					
1	0.05	0.10	2.53×10^{-14}	40.08	52.87
2	0.03	-0.19	2.43×10^{-14}	40.07	52.86
3	-0.04	0.24	2.09×10^{-14}	40.00	52.79
4	0.00	0.40	2.27×10^{-14}	40.04	52.83
5	0.01	-0.41	2.21×10^{-14}	40.03	52.82
total ring	6.10×10^{-13}	41.47	54.30
spiral arm H II regions					
6	-0.08	1.93	2.45×10^{-15}	39.07	51.86
7	-0.19	-1.91	1.14×10^{-15}	38.74	51.53
8	0.05	-3.12	9.35×10^{-16}	38.65	51.44
9	0.25	-2.82	7.18×10^{-16}	38.54	51.33
10	0.30	1.34	2.75×10^{-15}	39.12	51.91
11	0.44	-0.81	8.36×10^{-16}	38.60	51.39
12	0.57	2.13	6.99×10^{-16}	38.52	51.31
13	0.66	3.32	9.91×10^{-16}	38.64	51.43

NOTE.—The $\text{Pa}\alpha$ photometry of the H II regions is through a $0.30''$ -diameter aperture (95 pc), whereas the total flux of the ring is through a $2''$ -diameter aperture (≈ 620 pc). These values have not been corrected for extinction.

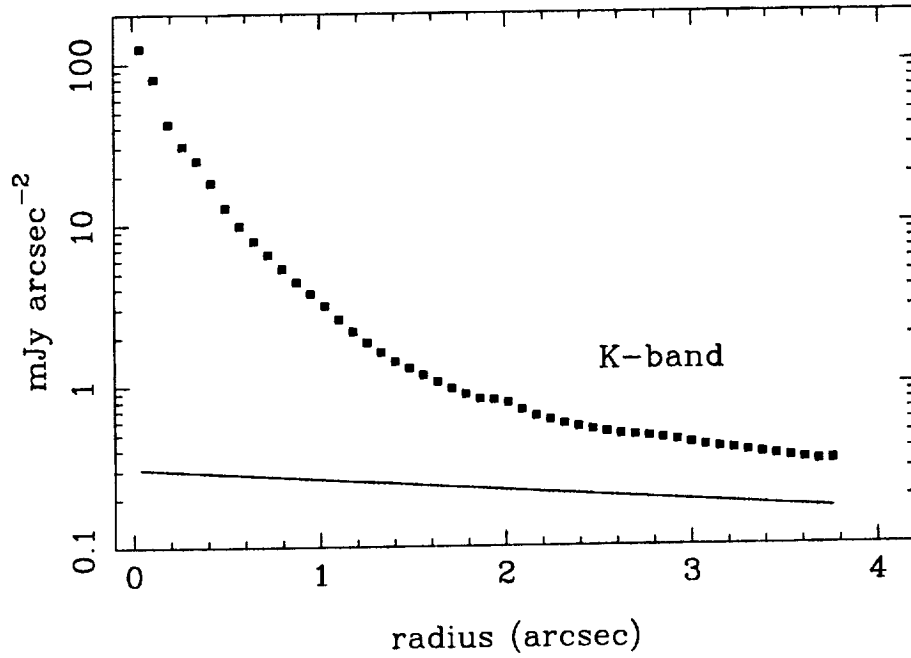
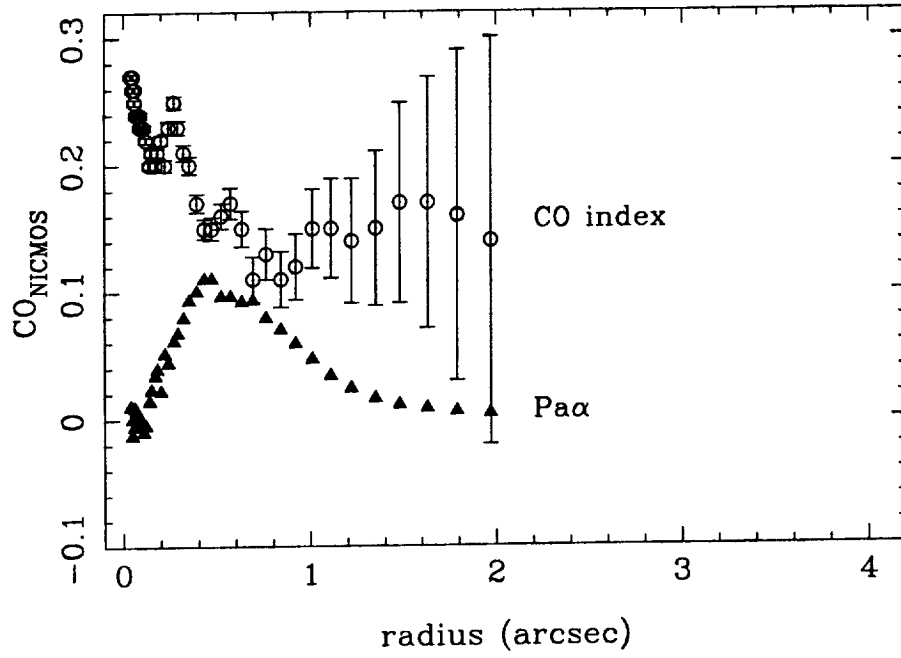


FIG. 4.— *Upper panel:* CONICMOS surface brightness profile. For comparison we also plot the Pa α profile (in arbitrary units) to show the location of the ring of star formation. *Lower panel:* NIC2 F222M (K-band) surface brightness profile. The solid line is the fit to an exponential disk (see Section 3.3.2 and Figure 7).

2.3. Near-Infrared Spectroscopy

Near-infrared spectra were obtained at Steward Observatory's 2.3-m Bok Telescope on Kitt Peak using FSPEC (Williams et al. 1993) with an orientation P.A. = 90°. The data were reduced as described by Engelbracht et al. (1998). The spectra were extracted from a $2.4'' \times 6.0''$ region centered on the galaxy nucleus and were flux-calibrated using ground-based imaging data. The J -band spectrum at a resolution of ~ 800 is shown in Figure 5 (upper panel), while spectra in the H and K bands at a resolution of ~ 3000 are shown in Figure 5 (middle and lower panels respectively). We have used the procedures discussed in Engelbracht et al. (1998) to subtract a stellar continuum, so that accurate measurements can be made of faint lines that might otherwise be affected by stellar absorption features. In Table 3 we present emission line fluxes. Our detections of the (1-0)S(0) and (2-1)S(1) lines of H_2 are supported by weak detections of the same lines by Puxley & Brand (1994).

The spectra also allow us to determine the CO index to quantify the depth of the first overtone absorption bands at $2.3\mu\text{m}$. Using the method and calibration discussed by Engelbracht et al. (1998), the CO index is 0.23, substantially stronger than for normal old stellar populations found in the nuclei of non-starbursting galaxies. Our determination that the CO absorption is stronger than expected for a "normal" galaxy nucleus is in agreement with previous work (Ridgway, Wynn-Williams, & Becklin 1994; Puxley & Brand 1994 as discussed by Goldader et al. 1997).

3. DISCUSSION

3.1. The extinction

Before we interpret the properties of NGC 1614, we need to apply an extinction correction. The extinction to the nucleus of NGC 1614 has been estimated a number of times. Some works (e.g., Neff et al. 1990; Shier, Rieke, Rieke 1996) have found relatively small values for the visual extinction ($A_V = 3 - 5$ mag with a foreground screen model) from optical and infrared colors, and infrared emission lines. Puxley & Brand (1994) used optical and near infrared hydrogen recombination lines, and claimed that the extinction to NGC 1614 could not be modeled with a simple foreground screen model. Instead they used a composite model (mixture of dust and gas, and a foreground screen) and inferred a total extinction in the optical of $A_V \simeq 11$ mag. Ho, Beck, & Turner (1990) derived a relatively large extinction between $\text{Br}\gamma$ and $\text{Br}\alpha$, but their result is subject to significant calibration uncertainties (see also Puxley & Brand 1994).

Using the fluxes of the two [Fe II] emission lines at $1.257\mu\text{m}$ and $1.644\mu\text{m}$ (whose ratio is largely independent of nebular conditions) and the hydrogen recombination lines $\text{Pa}\beta$ and $\text{Br}\gamma$ and a foreground dust screen model, we find values of the extinction to the gas in the K -band of $A_K = 0.40 - 0.49$ mag, corresponding to $A_V \sim 4$ mag. A comparison of dust models (from Witt, Thronson, & Capuano 1992) with the simple foreground screen model (c.f., the analysis of NGC 253 by Engelbracht et al. 1998) shows that the correction needed for all the infrared lines ([Fe II] $1.26\mu\text{m}$, [Fe II] $1.64\mu\text{m}$, $\text{Pa}\beta$ and $\text{Br}\gamma$) and the broad-band colors is similar. Thus a fore-

ground dust screen model (with extinction in the K -band of $A_K = 0.4 - 0.5$ mag) is a good approximation for the near-infrared extinction to the ionized gas. This approximation may not give the correct extinction in the optical, but we do not use any optical data for our study of the star formation properties of this galaxy.

The infrared $H - K$ color map (Figure 2 and also the close-up in Figure 6) shows that the actual distribution of the extinction is quite patchy. If we assume an intrinsic color $H - K = 0.25$ for the stellar population and the Rieke & Lebofsky (1985) extinction law, we find values of the K -band extinction to the stars of $A_K = 0.3 - 0.4$ mag to the east of the center of NGC 1614, whereas the K -band extinction to the west is higher, ranging between approximately 0.2 and 1.2 mag. The $H - K$ color of the nucleus (through a $0.76''$ -diameter aperture) is 0.41, which would imply a K -band extinction of $A_K = 0.3$ mag.

Compared with other dusty starbursts, the levels of extinction in NGC 1614 are low. We can determine the near infrared properties of the nucleus of NGC 1614 reasonably accurately by taking an average extinction of $A_K = 0.5$ mag and making a first order correction by assuming a simple foreground screen of dust. This value for the extinction agrees well with foreground screen model of Puxley & Brand (1994), $A_K = 0.43$ mag. They show that an underestimate of the Ly continuum by about 20% may result compared with more sophisticated models. However, from the combination of our slightly higher assumed extinction level and other minor differences, our derived Ly continuum is similar to the value they feel is most accurate. In general, if there are regions of very heavy extinction, or where the extinction is optically thick at the wavelengths of our observations, then we would have underestimated the starburst parameters. Our conclusions about the galaxy would become stronger with this error corrected.

The relatively modest extinction in a face-on starburst is an important advantage for studies of NGC 1614. The foundation for much of this paper is the resulting possibility to determine the starburst properties more reliably than for most other well-studied examples.

3.2. Morphology

The NICMOS images provide important new insights to the morphology of the starburst in NGC 1614. Figure 2 presents from the upper left corner and clockwise, the optical WFPC2 F606W image, NIC2 F160W (H -band), NIC2 F160W - NIC2 F222M ($H - K$ color map), and continuum subtracted $\text{Pa}\alpha$ image. The field of view of these images is $19.2'' \times 19.2''$. Figure 6 presents close-ups of the central regions ($8'' \times 8'' \simeq 2.5 \text{ kpc} \times 2.5 \text{ kpc}$) as in Figure 2.

The nucleus of NGC 1614 is extremely luminous, with an H -band absolute magnitude measured through a $0.76''$ -diameter aperture of $M_H = -23$ mag (corrected for extinction). The bright infrared nucleus is surrounded by a number of fainter sources and similar sources lie along the spiral arms. These objects are probably stellar clusters. We measured H -band luminosities (see Table 4) ranging up to $M_H = -17.2$ mag for the brightest sixteen clusters (excluding those located in the vicinity of the bright nucleus), similar to the cluster luminosities measured in Arp 299 (Alonso-Herrero et al. 2000a) and other luminous and ultraluminous infrared galaxies (Scoville et al. 2000). Neff

TABLE 3
LINE FLUX MEASUREMENTS

λ_{vac} (μm)	species	flux ($10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$)
1.0941	Pa γ	8.2 ± 0.6
1.2570	[Fe II]	3.9 ± 0.2
1.2822	Pa β	13.4 ± 0.3
1.5339	[Fe II]	0.5 ± 0.2
1.6114	Br13	0.9 ± 0.3
1.6412	Br12	0.7 ± 0.2
1.6440	[Fe II]	4.4 ± 0.2
1.6774	[Fe II]	0.5 ± 0.2
1.6811	Br11	1.7 ± 0.3
1.7367	Br10	1.6 ± 0.1
2.0338	H ₂ (1,0)S(2)	0.3 ± 0.1
2.0587	HeI	2.0 ± 0.1
2.0735	H ₂ (2,1)S(3)	0.3 ± 0.1
2.1218	H ₂ (1,0)S(1)	1.0 ± 0.1
2.1542	H ₂ (2,1)S(2)	< 0.2
2.1661	Br γ	4.0 ± 0.1
2.2233	H ₂ (1,0)S(0)	0.3 ± 0.1
2.2477	H ₂ (2,1)S(1)	0.2 ± 0.03

TABLE 4
CLUSTER PHOTOMETRY IN THE *H*-BAND.

#	$\Delta \text{ R.A.}$ (s)	$\Delta \text{ Dec.}$ ($''$)	m_{F160W}	$m_{1.60} - m_{2.22}$	M_H
1	-0.47	-0.66	18.7	0.56	-15.4
2	-0.43	-1.82	19.1	0.32	-15.0
3	-0.42	-3.49	18.9	0.52	-15.2
4	-0.42	0.34	17.5	0.44	-16.6
5	-0.31	1.45	16.9	0.38	-17.2
6	-0.27	2.42	18.8	0.05	-15.3
7	-0.21	-8.71	18.6	0.36	-15.4
8	-0.16	2.41	18.2	0.69	-15.8
9	-0.13	2.04	20.0	1.94	-14.0
10	-0.10	1.37	17.9	0.28	-16.1
11	-0.01	2.81	18.9	0.39	-15.1
12	-0.08	-2.23	17.5	0.47	-16.5
13	0.07	1.70	17.0	0.84	-17.0
14	0.16	1.04	18.1	0.70	-15.9
15	0.30	1.44	19.3	1.18	-14.8
16	0.52	-0.08	18.9	0.52	-15.1

NOTE.—Cluster photometry is through a $0.61''$ -diameter aperture (corrected for aperture effect). The $m_{1.60} - m_{2.22}$ color is similar to a ground-based $H - K$ color.

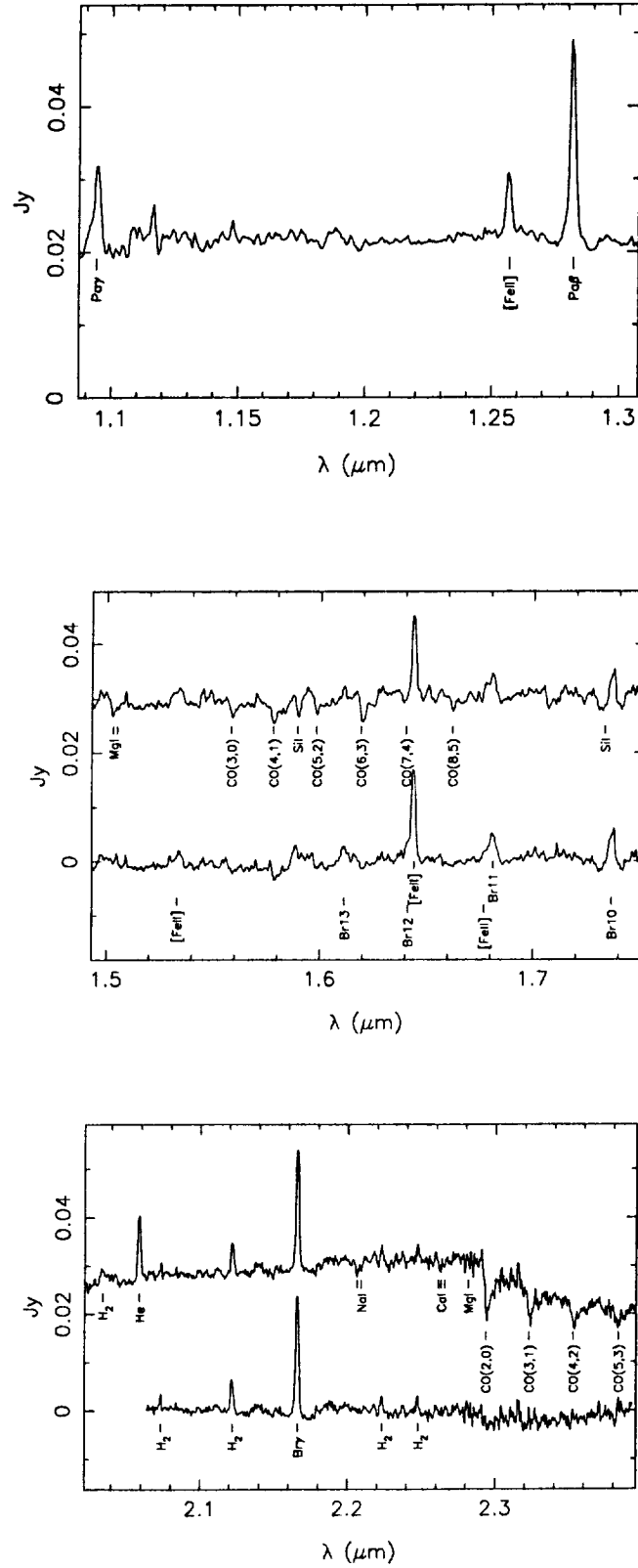


FIG. 5.— Flux calibrated *J*-band spectrum (upper panel), *H*-band spectrum (middle panel) and *K*-band spectrum (lower panel). The lower spectra in the panels for *H* and *K* are after subtraction of a stellar continuum and show the relative emission line strengths more clearly.

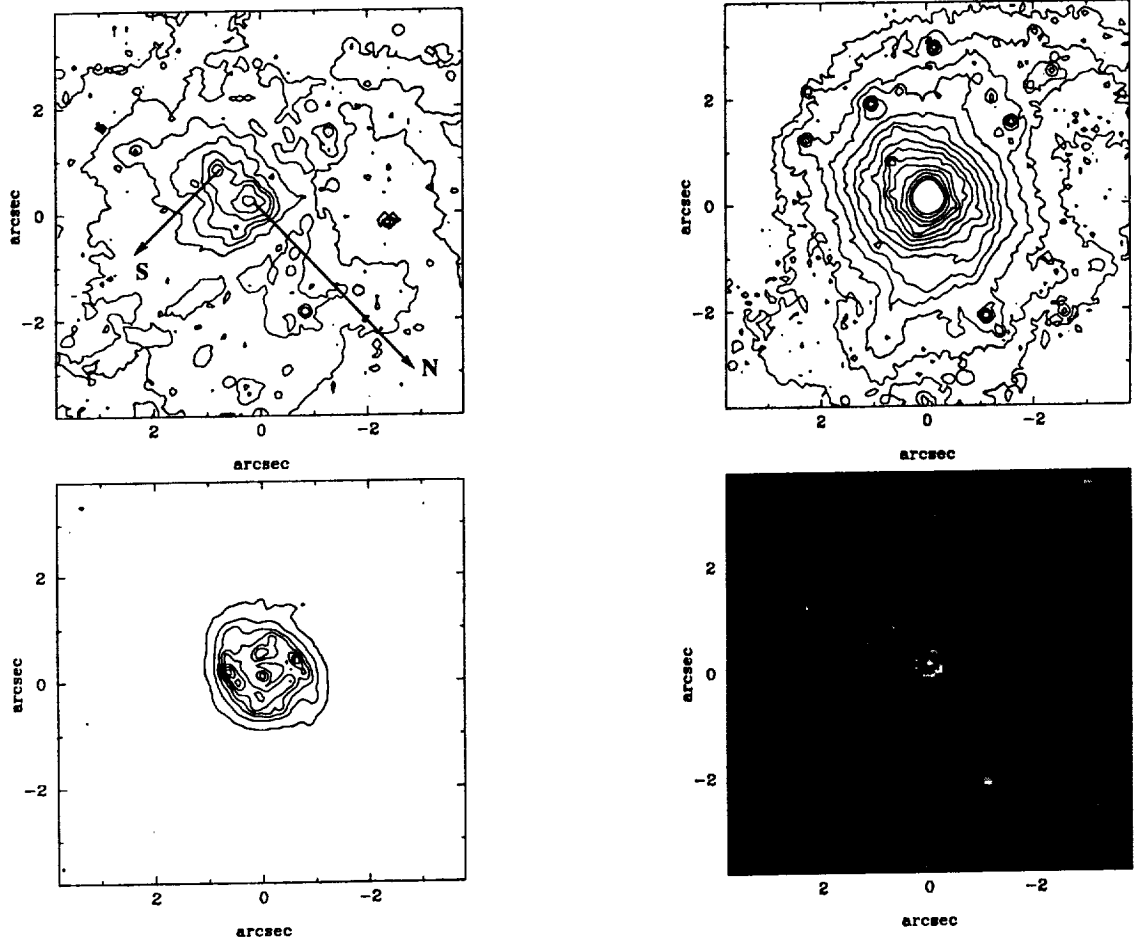


FIG. 6.— Close ups of the central $8'' \times 8''$. From the top left panel and clockwise: contour plot on a linear scale in the WFPC2 F606W filter, contour plot on a linear scale in the H -band (NIC2 F160W image), grey-scale $H - K$ color map (dark means regions with higher extinction, grey scale as in Figure 2) and contour plot of the continuum-subtracted emission line $\text{Pa}\alpha$ (NIC2 F190N - NIC2 F187N). The orientation for all the images is north up, east to the left. We indicate the position of the nucleus (N) and the secondary nucleus (S) in the WFPC2 F606W panel.

et al. (1990) noted the presence of a knot some $10''$ SW of the nucleus in a B -band image (figure 2 in their paper), and suggested that it could be interpreted to be fragments of a second galaxy. This knot (tentatively identified with cluster #7, Table 4) is on the edge of our NIC2 F160W image. It is most likely to be another stellar cluster from its observed luminosity.

Ground-based imaging shows the nucleus of the galaxy to be elongated at position angle 39° (e.g., Mazzarella & Boroson 1993). The WFPC2 F606W image resolves the central $2''$ of NGC 1614 into two prominent sources at a similar position angle (see Figure 6). The brighter of these sources coincides with the infrared nucleus. The other optical source lies at the position of a secondary peak in the infrared images to the NE of the nucleus, but it is far less prominent in the infrared than in the F606W image. Its H -band luminosity is about 30 times fainter than the primary nucleus ($M_H = -18.5 \pm 0.4$ mag; the error accounts for the uncertainty in the determination of the underlying background because of its proximity to the bright nucleus). The H -band absolute magnitude of the secondary peak is a magnitude or more brighter than the brightest of the stellar clusters, suggesting that it is the nucleus of an interacting small galaxy. The small extinction toward the secondary nucleus, as indicated by its blue color from optical to infrared, places it in front of the main nucleus and the activity around it (see Figure 6).

The CO band in the primary nucleus is very strong as shown by both our spectroscopy (Section 2.3) and imaging (Figure 4), much stronger than expected for an old stellar population. The most plausible explanation for this behavior is that the light from this nucleus is dominated by red supergiants that are the product of a starburst of age 10 or more million years. As shown in Figure 4, outside the starburst ring the CO index assumes a value appropriate to an old stellar population, presumably that of the underlying galaxy.

The $\text{Pa}\alpha$ line emission image reveals a nuclear ring of star formation with an approximate diameter of 650 pc. The $\text{Pa}\alpha$ morphology is remarkably similar to the 6 cm radio map (Neff et al. 1990). Although the two available mid-infrared images (Keto et al. 1992; Miles et al. 1996) do not agree in detail, they do show that the emission in the central part of the galaxy is confined to a $2''$ diameter region. The image of Miles et al. (1996), which should have higher angular resolution and signal to noise, suggests that the emission arises from the ring seen in $\text{Pa}\alpha$.

Comparison of small aperture ($\sim 5''$ diameter) ground-based photometry (Rieke & Low 1972; Lebofsky & Rieke 1979; Carico et al. 1988) with the IRAS fluxes (in a $45''$ by $250''$ beam) shows that the infrared emission of the entire galaxy is strongly concentrated into the central region. In fact, if approximate corrections are made from the ground-based to IRAS effective wavelengths and for the wavelength weighting introduced in IRAS to reduce color corrections to the fluxes, more than 80% of the total infrared flux at $12 \mu\text{m}$ originates in the nucleus, and hence, from the Miles et al. (1996) image, primarily in the circumnuclear ring. At $25 \mu\text{m}$, making similar corrections to the measurement by Lebofsky & Rieke (1979), we find about 75% of the total flux to originate in the nucleus. Given the relation between far infrared and radio fluxes, we can also estimate the central concentration in the far

infrared from radio data. We compare the survey results by Griffith et al. (1995) in a 4.2 arcmin beam at 6 cm with the VLA map of the nucleus reported by Neff et al. (1990). We have corrected the flux scale in the latter reference upward by 11%, as they suggest. We find that $\sim 60\%$ of the 6 cm flux lies in the nuclear ring. These three estimates are consistent in stating that about 70% of the far infrared luminosity arises from the nuclear region. In the following, we can ascribe most of the far infrared luminosity to the circumnuclear ring of H II regions.

The integrated far infrared luminosity indicates a star formation rate of $52 M_\odot \text{ yr}^{-1}$ from equation (3) of Kennicutt (1998). If 70% of this star formation occurs in the nucleus, we predict a level there of $36 M_\odot \text{ yr}^{-1}$. The $\text{Pa}\alpha$ luminosity in the circumnuclear ring (see Table 2) indicates, after correction for reddening, a star formation rate of $\sim 36 M_\odot \text{ yr}^{-1}$ from equation (2) of Kennicutt (1998), in perfect agreement.

The H II regions in the ring of NGC 1614 are extremely luminous with an equivalent ionizing luminosity an order of magnitude greater than that of 30 Doradus. A similar rich population of bright H II regions has been found in the luminous starburst in Arp 299 (see Alonso-Herrero et al. 2000a). The H II regions in the spiral arms are weaker than those in the ring, but still exceedingly luminous. Those listed in Table 2 are all similar in luminosity to 30 Dor (for which $\log L_{\text{Pa}\alpha} \sim 38.8 \text{ erg s}^{-1}$; Kennicutt, Edgar, & Hodge 1989). 30 Dor is usually considered the prototype *super-H II* region. Such objects are very uncommon in normal galaxies (e.g., Kennicutt et al. 1989; Rozas, Beckman, & Knäpen 1996). The existence of so many comparable to 30 Dor and even with greater ionizing luminosity appears to be associated with strong starbursts (see Alonso-Herrero et al. 2000a).

Just outside the ring of H II regions, the $H - K$ extinction map shows a partial ring of high extinction. This ring is obliterated to the NE due to the overlying secondary nucleus, but otherwise it can be seen for more than 220° . It traces the dense interstellar molecular material as discussed in the following section.

The molecular hydrogen appears to extend from the ring of H II regions into the molecular cloud (see Figure 3). The detection of the (2-1) S(3) line at $2.0735 \mu\text{m}$ and the (2-1) S(1) line at $2.2471 \mu\text{m}$ (the latter line both in our spectrum and in that of Puxley & Brand 1994) suggests that a significant fraction of the emission is due to fluorescence in low density gas, for which the ratio of these lines to the $2.12 \mu\text{m}$ line is ~ 0.5 (e.g. Black & van Dishoeek 1987; Sternberg & Dalgarno 1989). The relative H_2 line strengths are very similar to those in NGC 253 (Engelbracht et al. 1998), for which we derived that the excitation was probably shared between fluorescence and shocks, with nearly 2/3 of the total near infrared H_2 luminosity from the former mechanism. The morphology suggests that at least some of the H_2 originates at a shock penetrating into the molecular ring from the H II ring. Spectra of higher signal to noise and angular resolution will be needed to sort out the excitation conditions for the H_2 in more detail.

Figure 7 summarizes the distribution of starlight on a large scale. We have used ellipse fitting to generate surface brightness profiles from the NICMOS K -band image (Figure 4) and from a ground-based image (Shier et al. 1996). These profiles join smoothly and trace the surface bright-

ness to $20''$ radius (> 6 kpc). The galaxy is dominated by an exponential disk with a scale length of $6.3''$ (1.95 kpc) from a radius of $5''$ (1.6 kpc) outward. Within a radius of $3''$ (1 kpc), there is a bright central source fitted well by an $r^{1/4}$ law with a scale length of $1.14''$ or 350 pc. At least in the innermost arcsec this region is dominated by the output of the newly formed stars and not by a traditional bulge of old stars.

Combining the results reported above, NGC 1614 appears to be a textbook example of a propagating starburst that started in the nucleus of a late type, large spiral galaxy, has grown outward to a radius of ~ 300 pc, and is potentially still growing into a circumnuclear nuclear ring of molecular material just outside this radius (see also discussion in Section 3.4). This picture will be made more quantitative in a following section where we carry out evolutionary synthesis modeling of the starburst. Our data re-emphasize the result of Neff et al. (1990) that the activity in this galaxy is dominated by star formation and not by an AGN – there is no compact nuclear source either in the near or mid infrared, the emission lines are all narrow, and correlations observed in star forming regions such as the ratio of hydrogen recombination lines to far infrared luminosity appear to hold in NGC 1614. An interesting additional result is that the starburst is accompanied by a number of *super-H II* regions in the spiral arms of the galaxy. The presence of a secondary nucleus out of the plane of NGC 1614 suggests that all this activity has been triggered by an interaction with a smaller galaxy, which has by now largely been destroyed. There is further evidence for a merger from the tidal tails in the outer structure of NGC 1614 (Figure 1).

3.3. Mass

An aperture of diameter $2''$ (620 pc at the galaxy distance) includes the starburst and molecular ring. To understand the behavior in these regions, we need to determine the total mass and the mass of various constituents within this aperture. We first estimate the dynamical mass and then show that it is virtually all accounted for by the population of old, pre-starburst stars. The mass budget leaves very little for the starburst and molecular gas, as summarized in Table 5. This budget is strongly incompatible with the standard conversion of CO to gas mass and also challenges starburst models using conventional forms of the initial mass function.

3.3.1. Dynamical mass

Shier et al. (1996) modeled the velocity dispersion measured in the $2.3\mu\text{m}$ CO band head to derive the dynamical mass for a 1000 pc ($3''$) diameter region in NGC 1614. They considered three models for the stellar distribution: two bulge models and a disk model. The mass was only weakly dependent on which model was used for its derivation, although the mass in the disk model would be about twice that in the bulge ones if the disk were assumed to be at the inclination we find for the circumnuclear ring. However, since the K -band surface brightness profile of the inner 2-arcsec radius is well fitted with an $r^{1/4}$ law (see Figure 7), here we adopt the highest value for the spherical geometry (bulge) models of Shier et al. (1996), $1.8 \times 10^9 M_{\odot}$, and make an approximate correction in

proportion to diameter to the $2''$ diameter region which is thus indicated to have a mass of $12 \pm 4 \times 10^8 M_{\odot}$.

An independent estimate of the mass in the central region of NGC 1614 can be obtained using the Br γ spectroscopy presented in Puxley & Brand (1999), and our knowledge of the morphology and size of the emitting region (a ring). It is expected that the ring is associated with a Lindblad resonance or other similar dynamical feature and is close to round. Puxley & Brand (1999) detected two peaks of line emission separated by 151 km s^{-1} . We have obtained the ring rotational velocity by modeling the line profile expected for a rotating ring, convolved with a Gaussian to represent both the instrumental profile (resolution 39 km s^{-1}) and the dispersion within the beam. We find models with dispersions between 38 and 64 km s^{-1} fit equally well as the double Gaussian used by Puxley & Brand. In all the satisfactory models, the peak rotational velocity is very close to 1.4 times the velocity that would have been deduced just from the separation of the Gaussians fitted by Puxley and Brand. That is, the rotational velocity is 106 km s^{-1} , uncorrected for inclination. The total rotational velocity is determined by de-projecting for an inclination of $i = 51^\circ$ (determined from the observed ellipticity and an assumption that the ring is round).

From the H -band morphology we know that the mass is symmetrically distributed inside the H II ring, and therefore we can use the virial theorem in its simplest form to convert the rotational velocity to a mass. The conversion depends weakly on the mass distribution. Given the good fit of the $r^{1/4}$ model to the starlight in the center of the galaxy (see Section 3.2), coupled with the large mass represented by these stars (see next section), we have assumed a spherically symmetric mass distribution. We find that the total mass in a region with diameter $2'' \sim 620$ pc is $14 \times 10^8 M_{\odot}$. The mass for a spherically symmetric distribution lies midway between the minimum possible value, for a thin disk, and the maximum, for a thin and narrow ring. The total range between these two extremes is a factor of two (i.e., $\sim \pm 40\%$). Both because the situations at the extremes tend to be unstable and because of the observational evidence for a massive stellar spheroid within the ring, the systematic errors in our mass estimate should be much smaller than this range.

For the following we adopt the average of the two measures of $\sim 13 \times 10^8 M_{\odot}$ as the best estimate of the mass in the starburst region, with an upper limit of $20 \times 10^8 M_{\odot}$. Not only is this value based on two independent and consistent determinations, but also our extinction data indicate that the galaxy is optically thin at the wavelengths and in the regions critical for the mass determinations. Thus, the mass should be measured reliably.

3.3.2. Mass in old stars

To estimate the mass in old stars within the star forming region, we used the K -band fit to the surface brightness profile outside the ring of star formation (see Figure 7). The exponential disk is assumed to account for the old stars present in the galaxy before the strong episode of star formation seen today. The disk fit was extrapolated to the center of the galaxy to estimate the contribution of old stars hidden by the output of the starburst. No extinction correction was applied, since the extinction to the disk is unknown and in any case is likely to be less

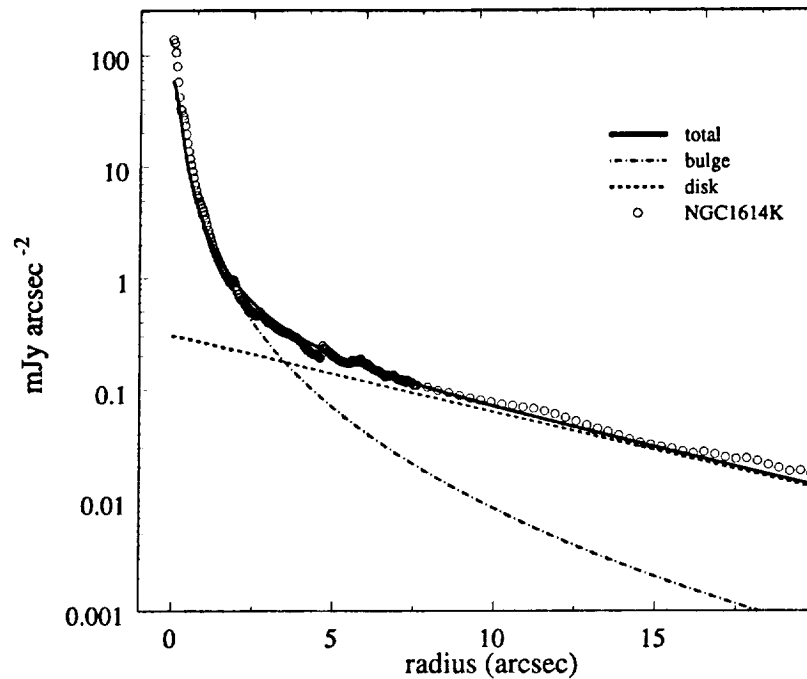


FIG. 7.— Surface brightness profile at K , combining NICMOS and ground-based images. The profile has been fitted with a combination of an exponential for the disk and an $r^{1/4}$ law for the central region.

TABLE 5
MASS BUDGET SUMMARY FOR THE NUCLEAR RING.

Component	Estimate*	Adopted*
Total dynamical mass		13
– From stellar velocity dispersion	12	
– From $P\alpha$ ring rotation	14	
Mass in old stars		12
Modeled starburst mass		5.5
Molecular gas mass		3
– From standard CO conversion	48	
– From extinction	$\geq 1 - 2$	
– From Toomre Q condition	≤ 4	
– For optically thin CO	2	

NOTE.—* units of $10^8 M_{\odot}$

than the already modest extinction (at K) to the nucleus. We estimated 1.2 mJy of K -band light is emitted by the old population within the central $2''$. Using the light-to-mass ratio derived for spiral galaxy disks by Thronson & Greenhouse (1988) (corresponding to $M/L_V \sim 1.4$), we find that the old stars account for $M_{*,\text{old}} \sim 12 \times 10^8 M_\odot$.

There is substantial evidence that the M/L for spiral disks is very similar from galaxy to galaxy and in accordance with the values derived from Thronson & Greenhouse (e.g., Bottema 1993; 1999). In fact, the widely applied Tully-Fisher relation probably depends on the uniformity of M/L in spiral disks (Aaronson, Mould, & Huchra 1979). Even if we assume that it is at the extreme low side of the dispersion in the Tully Fisher relation, the mass in the disk of NGC 1614 is unlikely to be more than 30% lower than our estimate. That is, assuming the lower limit $M/L_V \geq 1.1$, a lower limit to the disk mass in the nuclear region is $9 \times 10^8 M_\odot$. Our estimate ignores the mass of any bulge of old stars hidden within the central starburst region, and hence this lower limit is quite conservative.

Comparison of the mass in old stars with the dynamical mass of $13 \times 10^8 M_\odot$ provides a difficult constraint. This problem cannot be relieved significantly by enlarging the region under consideration. For example, within a $3''$ diameter region, the flux from the exponential disk model is 1.9 mJy, corresponding to a lower limit on the mass in old stars of $14.5 \times 10^8 M_\odot$, which includes virtually all the dynamical mass within this diameter also.

3.3.3. Mass of ISM from standard CO to H_2 conversion

Use of the standard procedure for estimating the mass in the interstellar medium from CO measurements is strongly inconsistent with the mass budget implied by the dynamics and the old stellar population; see Table 5. Scoville et al. (1989) made observations of the nuclear region in the ^{12}CO J=1-0 line. These results have been re-analyzed by Scoville et al. (1991) and Bryant & Scoville (1999); our discussion is based primarily on the last reference. The nuclear CO source is described as being unresolved with a diameter $< 3''$. Most of the material is probably located in the ring of strong extinction revealed in our $H-K$ images, which is $2''$ in diameter. Bryant & Scoville (1999) use a "standard" conversion of CO emission to total mass ($H_2 + \text{He}$) of molecular gas of $N(H_2)/I_{\text{CO}} = 2.25 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$, corrected by a factor of 1.36 to allow for the mass in helium. They deduce a nuclear molecular mass of $48 \times 10^8 M_\odot$, nearly four times the total dynamical mass! Further details of the conversion (but with a slightly higher standard factor) can be found in Sanders, Scoville, & Soifer (1991).

The use of the standard conversion factor in intense starbursts has come under question previously. Maloney & Black (1988) suggested that it should substantially overestimate the molecular masses because of the relatively high densities and temperatures of the molecular clouds in these regions. Shier, Rieke, & Rieke (1994) determined the dynamical mass with near infrared spectroscopy of the $2.3\mu\text{m}$ CO bandhead in the nuclei of a number of luminous starburst galaxies and found that the masses of gas were overestimated by the standard conversion by factors of 4–10. Solomon et al. (1997) and Downes & Solomon (1998) concluded the standard factor may be high by a factor of five in starbursts, based on a comparison of the dynamical

mass and gas mass from far infrared measures. Lisenfeld, Isaak, & Hills (2000) used submillimeter measurements of the emission by cold dust to argue that the CO-deduced mass is typically 2–3 times higher than would be deduced from the thermal emission. Dunne et al. (2000) point out that such an increase is one of the possible explanations for apparently large values of M_{H_2}/M_d in some strong merging/starburst galaxies. However, agreement has not been reached as illustrated, for example, by the use of the standard factor by Bryant & Scoville (1996, 1999).

3.3.4. Independent estimates of the molecular mass

In NGC 1614, an independent test of the large molecular mass deduced from the standard conversion can be based on the mm-wave CO line profile. Casoli et al. (1991) have published a profile in a $44''$ diameter beam that shows the full width at 20% intensity to be $\sim 300 \text{ km s}^{-1}$. The line profile of Sanders et al. (1991) in a $55''$ beam has a full width at 20% intensity of 390 km s^{-1} . Scoville et al. (1989) show that about 30% of the emission in these beams would have been from the central compact source. If the mass of this region were $5 \times 10^9 M_\odot$, the line width would be $\sim 400 \text{ km s}^{-1}$ or greater for this central 30% component, which would be very difficult to reconcile with the lack of strong, broad wings in the observed profile.

We have made another estimate of the amount of molecular gas, based on our discovery of an extinction shadow due to a circumnuclear molecular ring. We use the ratio of ^{18}CO emission to H_2 from the study of molecular clouds by Goldsmith, Bergin, & Lis (1997) and the relation between A_V and ^{18}CO from Alves, Lada, & Lada (1999) to relate the extinction in this ring to its mass. From our data, we estimate that the shadow of the molecular ring subtends an annulus between radii of 0.5 and $1''$ with a typical extinction level of $A_V \sim 12 \text{ mag}$. Because the extinction is only effective in the foreground of the stellar population, we made the assumption that the source is symmetric along the line of sight and therefore doubled the mass estimates derived from the relations cited above. Our value should probably be taken as a lower limit: we would underestimate the extinction if stars are mixed with the obscuring gas (or if some stars lie in front of it, or the obscuration is clumpy). Also, the reddening at H and K in the thickest parts of the ring is strong enough that optical depth effects might reduce the apparent extinction. Nonetheless, our value of $1 - 2 \times 10^8 M_\odot$ is well aligned with the dynamical mass and, in fact, a significantly higher value would create a serious problem in explaining the nuclear properties given the other constituents and their expected contributions to the mass.

An upper limit to the mass of interstellar material can be obtained from the discovery that this material is predominantly distributed in a circumnuclear ring, as shown both by the $\text{Pa}\alpha$ morphology and the extinction shadow of a ring sector seen in the color maps. Although this ring is currently the site of vigorous star formation as the starburst propagates outward, it must have originally been a semi-stable configuration. The Toomre stability parameter for gas in a plane is

$$Q = \frac{\kappa \sigma}{\pi \Sigma G} \quad (1)$$

where κ is the epicyclic frequency, σ is the cloud velocity

dispersion and Σ is the gas surface density. So that the gas remains in a disk and does not fragment into small clumps, $Q > 1$. Thus, we can derive an upper limit for Σ :

$$\Sigma < 470 M_{\odot} \text{pc}^{-2} \left(\frac{v_c}{100 \text{km/s}} \right) \left(\frac{310 \text{pc}}{r} \right) \left(\frac{\gamma}{2} \right) \left(\frac{\sigma}{10 \text{km/s}} \right) \quad (2)$$

where v_c is the circular velocity and $\gamma = \kappa r / v_c$. We have used a maximum value of $\gamma = 2$ for a solid body rotation curve. We assume a velocity dispersion of $\sigma = 20 \text{ km s}^{-1}$. This value was determined by extrapolating the observed cloud size/line width relation (Falgaron, Puget, & Pérault 1992) to a size of 100 pc and then doubling the width for good measure, to allow for possible extreme conditions in a galaxy nuclear region. Taking $M_g = 2\pi r dr \Sigma$ using $dr = 150 \text{ pc}$ (based on the ring width in the extinction shadow), we find a maximum mass of $M_g < 4 \times 10^8 M_{\odot}$. If there is a high dispersion component of material, the actual gas mass could be somewhat higher.

Another lower limit of $M_g > 2 \times 10^8 M_{\odot}$ can be computed by assuming the CO emission is optically thin (Bryant & Scoville 1996, equation A4).

3.3.5. Conclusions about the ISM in the nucleus of NGC 1614

Combining these arguments, the molecular mass in the nucleus is most likely $\sim 3 \times 10^8 M_{\odot}$, about 25% of the dynamical mass in this region. This mass is about 15 times lower than the $4.8 \times 10^9 M_{\odot}$ in molecular mass deduced from CO and the standard conversion by Bryant and Scoville (1999). Table 5 illustrates how tight the mass budget is. It seems unlikely that the molecular gas can be more than 1/10 the amount estimated from the standard conversion even if the dynamical mass is set to the upper limit of $20 \times 10^8 M_{\odot}$ and the mass in old stars to its lower limit of $9 \times 10^8 M_{\odot}$. In that case, it might be necessary to incorporate a significant change in the starburst initial mass function (see Section 3.5.2). Our results are in agreement with those of Shier et al. (1994), who estimated that the amount of gas in the nucleus of NGC 1614 was a factor of at least nine below the value from the standard conversion.

To accompany their estimate of a huge mass of molecular gas, Scoville et al. (1989) inferred the extinction in the nuclear region of NGC 1614 to be $A_V > 95 \text{ mag}$. They argued that much of the "action" in this region would be hidden from optical and even infrared observers unless there happened to be a particularly favorable line of sight. This picture of LIRGs and ULIRGs has gained wide credence, but the observations presented here are a serious caution. Not only do we find far less molecular mass, but more significantly for the "hidden action" model, we *do not* find anything approaching the high extinction deduced from the CO observations. An independent indication that the extinction is not hiding any significant action is the close correspondence between the star formation rates deduced from Pa α and far infrared luminosities, as discussed in Section 3.2.

3.4. The star formation properties

For our analysis of the star formation properties of NGC 1614, we will use the Rieke et al. (1993) evolutionary synthesis starburst models because they include a careful calibration of the CO stellar absorption band strengths against observational data. We have considered Gaussian bursts of 5 Myr duration (FWHM) with the peak of star formation at 5 Myr after the beginning time for the burst. NGC 1614 is a well known Wolf-Rayet (WR) galaxy (Vacca & Conti 1992; Schaerer, Contini, & Pindao 1999). The presence of WR features in star forming galaxies can only be explained with short bursts of star formation with durations of the order of a few million years (Leitherer & Heckman 1995), as used in our fit to the observed properties of the galaxy.

We used a truncated Salpeter IMF¹ which is virtually identical to IMF8 which Rieke et al. (1993) decided gave the best fit to the properties of M82, and has since been shown to fit other starburst galaxies well (Engelbracht et al. 1996, 1998). In Table 6 we summarize the properties of the central starburst of NGC 1614 that will be fitted with the evolutionary synthesis models.

The infrared luminosity will be taken as a lower limit to the bolometric luminosity of the galaxy. This assumption makes two errors in opposite direction. From the aperture measurements discussed in Section 3.2, up to about one third of the infrared luminosity of the galaxy may be produced outside the nuclear region. On the other hand, a significant amount of optical/UV energy must escape from the starburst before it is absorbed and re-emitted in the infrared, particularly given the patchy and relatively low level of extinction. The number of ionizing photons is from both the [Ne II]12.8 μm line flux of Roche et al. (1991), and the *HST*/NICMOS Pa α flux, the latter corrected for an average extinction of $A_K = 0.5 \text{ mag}$ and assuming case B recombination. Our estimate of the number of ionizing photons is in good agreement with the value from Puxley & Brand (1994) derived from measurements that included Br α , analyzed through detailed modeling of the extinction. It is also consistent with the upper limit established from the 3σ non-detection of the radio H α 92 hydrogen recombination line (Phookun, Anantharamaiah, & Goss 1998). To allow for the possibility of absorption of ionizing photons by interstellar dust, in the models we take the derived UV flux as a lower limit. The [Fe II] line ratios are similar to those detected in NGC 253 (Engelbracht et al. 1998) and are typical of those in supernova remnants. We estimated the supernova rate (SNr) from the [Fe II]1.644 μm luminosity (corrected for extinction) from this work and a new calibration between these two quantities (Alonso-Herrero et al. 2000b, in preparation).

Our best fit to the properties of NGC 1614 with a single burst of star formation is presented in Figure 8 (left panel). In this diagram the output of the model is normalized to the properties of NGC 1614 so the target quantity is unity. The model uses a mass in newly formed stars of $5.6 \times 10^8 M_{\odot}$ ($\simeq 0.4 \times M_{\text{dyn}}$). The derived age is between 5 Myr and 8 Myr after the peak of star formation, or 7 – 11 Myr measured from the rising half power of the assumed Gaussian star formation rate. This age is consistent with our failure to detect the 1.7 μm He line, which suggests (although it is not a strong result given the sig-

¹ $\phi(m)dm \propto m^{-2.35}dm$ from 1 to $80 M_{\odot}$, and $\phi(m)dm \propto m^{-1}dm$ from 0.1 to $1 M_{\odot}$.

TABLE 6
STARBURST MODEL CONSTRAINTS FOR THE STAR FORMING NUCLEAR RING.

Property	Value	Origin	Reference
Dynamical Mass	$1.3 \times 10^9 M_{\odot}$	IR spectroscopy	this work
Infrared Luminosity	$3 \times 10^{11} L_{\odot}$	IRAS	Goldader et al. (1997)
Ionizing photons (log)	54.5, 54.6 s^{-1}	[Ne II], Pa α	Roche et al. (1991), this work
K absolute magnitude	-23.6 mag	...	Engelbracht (1997)
SNr	0.3 yr^{-1}	[Fe II]	this work
CO index	0.23	IR spectroscopy	this work

NOTE.—The values of N_{Ly} (from Pa α), K -band absolute magnitude and SNr are corrected using an extinction of $A_K = 0.5 \text{ mag}$.

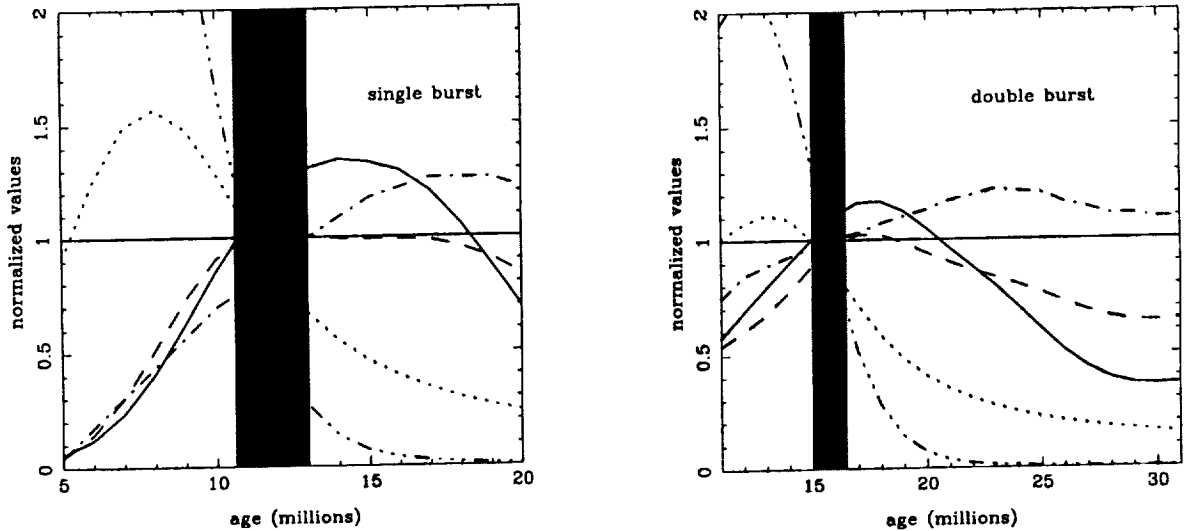


FIG. 8.— *Left panel.* Best fit to the properties of the central starburst of NGC 1614 for the short-duration Gaussian burst $\text{FWHM} = 5 \times 10^6 \text{ yr}$. *Right panel.* Best fit using a double Gaussian burst ($\text{FWHM} = 5 \times 10^6 \text{ yr}$). The elapsed between the two bursts is $5 \times 10^6 \text{ yr}$. In both Figures 8a and 8b, the solid line is the K -band luminosity, the dashed line is the SNr, the dot-dash line is the CO index, the dotted line is the bolometric luminosity and the dot-dot-dot-dash line is the number of ionizing photons. The age in the x-axis is the age from the beginning of the star formation episode. The peak of star formation occurs after 5 Myr. The shaded area shows the limiting starburst ages for a given fit.

nal to noise) that there are relatively few stars hotter than 40,000 K (Vanzi et al. 1996). All the observables except the CO index converge at the young age. The observed CO index appears to be too deep for such a young population.

The strong CO of this galaxy is more typical of a stellar population ten million years old or older. The discrepancy with the age of 5 – 8 Myr for the other starburst indicators suggests that this galaxy has experienced a more extended period of star formation than in our single burst. The simplest example would be a double burst. In Figure 8 (right panel) we show the best fit model obtained with two Gaussian bursts (both with FWHM = 5 Myr) separated by 5 Myr. Each burst uses 20% of the dynamical mass. As can be seen from this figure, the fit is excellent. The derived age is $10 - 11.5 \times 10^6$ yr after the peak of star formation of the first burst. A variety of other time dependencies of star formation are also likely to fit the data, but the minimum duration of the episode and the minimum mass required are both well constrained by the double burst model.

This starburst model coincides closely with the morphology of the galaxy. We find that the strong CO is concentrated in the nucleus (Figure 4, upper panel), and the modeling associates this feature with the older part of the starburst. Most of the ionizing flux is produced in the younger part of the starburst, and is physically located in the circumnuclear ring (Figure 6). From the starburst modeling and the diameter of the circumnuclear ring of H II regions, we can roughly estimate that the speed at which the starburst is propagating outward is $\sim 60 \text{ km s}^{-1}$.

3.5. The Initial Mass Function

3.5.1. Previous estimates of the IMF in starbursts

Rieke et al. (1980) found that evolutionary starburst models using the then-current form for the local IMF (Miller & Scalo 1979) had difficulty fitting the properties of M82 within the available dynamical mass. They suggested that the IMF in the starburst might be biased toward massive stars compared with the proposed local form. Since the low mass stars contribute most of the total mass in the IMF, but have no observable properties in a starburst, reducing their numbers is a plausible way to reconcile the masses. This possibility has been discussed at great length since. Rieke et al. (1993) reconsidered M82, experimenting with a broad variety of forms for the IMF and histories of star formation. They confirmed that the currently proposed forms for the local IMF (e.g., Scalo 1986) were inadequate and proposed their "IMF8" as a more satisfactory solution. IMF8 provides 4 – 5 times more stars in the $10 - 30 M_{\odot}$ range than does Scalo (1986) but drops toward higher masses to avoid overproduction of oxygen in very massive stars (Rieke et al. 1993).

In the last few years, modeling of the ultraviolet spectra of starburst galaxies has led to the conclusion that their IMFs have roughly the Salpeter slope at high masses (e.g., González-Delgado et al. 1999). Satyapal et al. (1997) modeled M82 with less complete evolutionary models than used by Rieke et al. (1993). They claimed that they could account for the K -band luminosity with a Salpeter IMF, avoiding the necessity to suppress formation of low mass stars compared with the local IMF. A problem with their

approach is that they did not demonstrate the simultaneous fitting of all the starburst constraints used by Rieke et al. (1993); it is relatively easy to fit a subset of constraints if the rest are ignored. Furthermore, because they assumed a foreground screen extinction model, the K -band luminosity they fitted is in fact a lower limit to the true luminosity, making their fits less demanding. Nonetheless, their success with a modified Salpeter IMF confirms independently the derivation of IMF8 to fit M82 by Rieke et al. (1993), as we show below.

The critical aspect of a starburst IMF constrained by luminosities and dynamical mass is the proportion of mass it places in the $10 - 30 M_{\odot}$ range that dominates the observable aspects of the starburst. Table 7 summarizes this proportion and that of more massive stars for the various forms of the IMF that have been used to fit starbursts. It shows the similarity of IMF8 and the modified Salpeter IMF, which are equivalent in fitting the primary starburst characteristics. However, IMF8 is to be preferred because its factor of two lower portion of very massive stars results in a proportionate reduction in the production of oxygen. Keeping the abundance of oxygen within the observational limits is a difficult constraint in starburst models (Rieke et al. 1993; Wang & Silk 1993). The other forms for the IMF produce significantly fewer $10 - 30 M_{\odot}$ stars. To first order, the dynamical masses required with them are just in the ratio of the proportions of these stars. Thus, if M82 can be fitted with $2.5 \times 10^8 M_{\odot}$ in a modified Salpeter IMF, it would require about $5 \times 10^8 M_{\odot}$ with a Miller-Scalo IMF, about 70% of the dynamical mass available and unlikely to be an acceptable fit once allowance is made for the mass of other constituents of the nuclear region. For NGC 1614, the Miller-Scalo IMF would take all the dynamical mass and the Scalo (1986) and Basu & Rana (1992) ones would require about twice the dynamical mass, all of which is clearly unacceptable.

Virtually all studies find the local IMF to fall more steeply toward high masses than the Salpeter form. Even Salpeter (1955) continued the simple power law to high masses only for simplicity, but at the same time called attention to an apparent high mass steepening: "It is not yet clear whether the steeper drop for masses larger than $10 M_{\odot}$ is a real effect, since in this region masses and bolometric corrections are not known very accurately and the number of such stars near the galactic plane is small." As with the rest of his work this statement has proven prescient. However, a Salpeter IMF has been shown to be an approximate fit in many situations outside the local neighborhood (e.g., Scalo 1998). It now appears that a better description of the M82 issue might be that the local IMF (or at least our estimates of it) may differ from the IMF we find in most regions of active star formation, including in starbursts like M82.

3.5.2. NGC 1614: a more extreme IMF?

We have emphasized that NGC 1614 is particularly well suited to studying starburst properties, given the relatively modest near infrared extinction and our favorable viewing of it at modest inclination. It has a well determined dynamical mass of $13 \times 10^8 M_{\odot}$ in the starburst region, as discussed in Section 3.2. However, the constituents in this region appear to sum to a significantly greater mass, $> 9 \times 10^8 M_{\odot}$ for the old stars plus $\sim 3 \times 10^8 M_{\odot}$ for

TABLE 7
PERCENTAGE OF MASS IN HIGH MASS STARS.

IMF	10 – 30 M_{\odot}	30 – 100 M_{\odot}
IMF8	14%	5%
Modified Salpeter	13%	9%
Original Salpeter	7%	5%
Miller & Scalo 1979	6.5%	3%
Scalo 1986	3%	1%
Basu & Rana 1992	3%	3.5%

the molecular gas plus $5.5 \times 10^8 M_{\odot}$ for the starburst using either a Salpeter IMF or IMF8. The total exceeds the dynamical mass by at least 35%. Unless there is substantial contamination of the disk outside the starburst by younger stars, these numbers suggest that the mass in the starburst may be overestimated. A further indication in the same direction is that the starburst plus remaining molecular gas in our nominal estimates account for 65% of the dynamical mass. Theoretical modeling suggests that instabilities will set in and a starburst will appear once the mass of gas reaches $\sim 20\%$ of the total in a galaxy nucleus (Wada & Habe 1992; Bekki 1995). These estimates are somewhat uncertain and may not apply strictly to the conditions in NGC 1614. However, they fall so far below the deduced mass of new stars and residual gas to suggest that the IMF in the NGC 1614 starburst is weighted toward massive stars, even compared with IMF8 or a modified Salpeter function. This behavior should be tested in studies of other extreme starbursts.

3.6. The star formation efficiency

The mechanism needed to account for the strong star formation in luminous mergers is a matter of debate. The two main competing models are: (1) cloud-cloud collisions which predict a large population of high mass stars to give rise to the high infrared luminosities (Scoville, Sanders, & Clemens 1986) (2) gravitational instability in nuclear gas disks, as favored by Taniguchi & Ohya (1998). The former model would predict a Schmidt law² with index $N = 2$, whereas the latter model predicts indices $N = 1 - 1.5$ as found for isolated galaxies and strong starbursts (Kennicutt 1998; Taniguchi & Ohya 1998).

From the Pa α luminosity of NGC 1614 (corrected for extinction) and using the relation between SFR and H α luminosity (Kennicutt 1998) we measured a SFR = $36 M_{\odot} \text{ yr}^{-1}$ in the ring and a SFR surface density of $\Sigma_{\text{SFR}} = 120 \pm 50 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, similar to, although slightly higher than, the earlier estimate by Kennicutt (1998) from the FIR luminosity and somewhat different parameters for the size of the emitting region ($\Sigma_{\text{SFR}} = 65 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$). The value of $\Sigma_{\text{SFR}} = 120 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ that we found for NGC 1614 is of the same magnitude as that of the giant H II region 30 Doradus (Kennicutt 1998), and the global star formation efficiency for this galaxy approaches 100% over a gas consumption period of 10^8 yr . Based on

the standard conversion, Kennicutt (1998) derived $N = 1.4 \pm 0.15$. If the mass in molecular gas is only $\sim 3 \times 10^8 M_{\odot}$, with a conversion of CO to H $_2$ mass a factor of ~ 15 lower than the standard value, one would derive $N = 2$ or more, as discussed by Kennicutt (1998) (with less gas, higher efficiency is needed). Thus, our results appear to favor the cloud collision explanation for the high rate of star formation.

3.7. Comparison with Simulations

Mihos & Hernquist (1994) explored via numerical simulations the merger of a large and a smaller galaxy, similar to our proposal for NGC 1614. From their simulation they predicted that in response to the tidal perturbation of the infalling satellite, the disk galaxy develops strong spiral arms. This non-axisymmetric perturbation causes large quantities of material to be funneled into the central regions, and as a result a strong burst of star formation is triggered lasting for up to 60 Myr. The predicted central starburst is very compact ($\simeq 350 \text{ pc}$ in radius) and contains some 85% of the total mass in newly formed stars.

Hernquist & Mihos (1995) carried out further simulations. They showed that the degree of central concentration of gas decreases markedly with the presence of a massive bulge. The relatively low dynamical mass in the central 620 pc of NGC 1614 indicates that it had little bulge prior to the collision, so it would be ideal for a strong central concentration of gas. Hernquist & Mihos (1995) state that the resolution of their calculations is inadequate to determine how the gas behaves once it has sunk into the central few hundred pc. However, from the behavior of NGC 1614, it appears that it must be further concentrated until instability is reached in the bottom of the potential well of the galaxy, leading to the initial stages of massive star formation.

As the starburst ages, supernovae begin to explode and winds develop that expand outward, compressing the remaining molecular gas surrounding the nucleus (e.g., Tenorio-Tagle & Muñoz-Tuñón 1997; Taniguchi, Trentham, & Shioya 1998). Gravitationally unstable shocked layers of interstellar gas may be produced in cloud cloud collisions and by the impact of these winds on incoming clouds. The resulting star formation appears to favor massive stars (Whitworth et al. 1994), possibly accounting for the suggestion of a high abundance of such stars in ex-

²The star formation rate density is a gas density power law, $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^N$, Schmidt (1959)

trème starbursts. The evidence we find that the starburst in NGC 1614 has expanded from the nucleus to the ring of H II regions and into the surrounding molecular ring is in agreement with this picture.

4. SUMMARY

We have used *HST*/NICMOS and WFPC2 imaging, ground-based near infrared spectra, and information from the literature to study the luminous infrared galaxy NGC 1614. The modest extinction to its starbursting nucleus, combined with our favorable viewing angle, make this galaxy ideal for probing the properties of its powerful starburst. We show that

- Star formation has propagated outward from the nucleus to a ~ 300 pc radius circumnuclear ring of massive H II regions.
- These circumnuclear H II regions are an order of magnitude more luminous than 30 Doradus, and H II regions in the spiral arms are similar in luminosity to 30 Dor. These regions are probably younger versions of the luminous stellar clusters also around the nucleus and in the spiral arms. The presence of so many extremely luminous H II regions and stellar clusters is similar to the behavior of other luminous starbursts.
- The ring of H II regions is surrounded by molecular gas. The mass in molecular gas appears to be

$\sim 1/15$ the prediction from the standard $^{12}\text{CO}/\text{H}_2$ ratio, with an upper limit of $1/10$ the standard ratio. The large levels of extinction predicted previously from the standard ratio are absent in NGC 1614.

- The mass budget for the starburst is very tight, suggesting that the proportion of massive stars is larger than predicted by a Salpeter IMF modified to turn over near $1 M_\odot$, or by the virtually identical IMF8 found to fit the starburst in M82 (Rieke et al. 1993). Until now, such IMFs have been adequate to fit the properties of all known starbursts.
- The high efficiency needed to convert the available molecular gas density into the observed density of star formation suggests that the starburst is propagating by cloud-cloud interactions and winds.
- The behavior of NGC 1614 is consistent with simulations for the interaction of a modest sized galaxy with a massive, late type spiral.

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